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On the intensity and spatial morphology of the 511 keV emission in the Milky Way

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Abstract. The positron emissivity of the Galactic bulge and disk, resulting from radioactivity of SNIa, is reassessed in the light of a recent evaluation of the SNIa rate. It is found that the disk may supply more positrons than required by recent SPI/INTEGRAL observations, but the bulge (where the characteristic e^+ annihilation line at 511 keV is in fact observed) only about 10%. It is argued that a large fraction of the disk positrons may be transported via the regular magnetic field of the Galaxy into the bulge, where they annihilate. This would increase both the bulge positron emissivity and the bulge/disk ratio, alleviating considerably the constraints imposed by INTEGRAL data analysis. We argue that the bulge/disk ratio can be considerably smaller than the values derived by the recent analysis of Knödlseder et al. (2005), if the disk positrons diffuse sufficiently away from their sources, as required by our model; this possibility could be soon tested, as data are accumulated in the SPI detectors. The success of the proposed scenario depends critically upon the, very poorly known at present, properties of the galactic magnetic field and of the propagation of low energy positrons in it.

Key words. Physical Processes: magnetic fields - ISM: cosmic rays, magnetic fields - The Galaxy: general - Gamma Rays: theory

1. Introduction

The origin of the Galactic electron-positron annihilation radiation has remained problematic ever since the original detection of its characteristic 511 keV line (e. g. Diehl et al. 2005 and references therein). In particular, recent observations of the line intensity and spatial morphology with the SPI instrument aboard INTEGRAL put severe constraints on its origin, since it appears that 1.5±0.1 10^{43} e^+/s are annihilated in the bulge alone and 0.3±0.2 10^{43} e^+/s in the disk, i.e. that the bulge/disk positron emissivity ratio is B/D ∼5 (Knödlseder et al. 2005). The most promising sources of positrons in the Galaxy apear to be type Ia supernovae, but "conventional" models of Galactic e^+ production through SNIa radioactivity fail to explain these features (see Sec. 2). This failure prompted suggestions of more "exotic" models, involving SNIc supernovae and γ-ray bursts (Nomoto et al. 2001, Cassé et al. 2004, Bertone et al. 2004, Parizot et al. 2004), low mass X-ray binaries (Prantzos 2004), millisecond pulsars (Wang et al. 2005), microquasars (Guessoum et al. 2005), and more exotic ones, like annihilation of light dark matter particles (Boehm et al. 2004, Ascasibar et al. 2005) and a tangle of light superconductiong cosmic strings (Ferrer and Vachaspati 2005); see Prantzos (2004), Diehl et al. (2005) or Knödlseder et al. (2005) for a critical discussion of those suggestions.

In this work we reasses the SNIa e^+ emissivity of the Galactic bulge and disk in the light of recent data, and we find that the sum of the two components is slightly larger than required from SPI measurements. This may be a coincidence, but we argue here that a large fraction of the disk positrons may be transported via the regular magnetic field of the Galaxy into the bulge, where they annihilate. This increases both the bulge positron emissivity and the bulge/disk ratio, alleviating considerably the constraints imposed by the recent SPI/INTEGRAL data analysis (Knödlseder et al. 2005). In fact, we argue that the SPI data are compatible with values of B/D as low as 0.5, because positrons can propagate away from their sources and fill a rather large volume, much larger than the relatively thin disks adopted in the analysis of Knödlseder et al. (2005). This property is crucial to the success of the scenario proposed here, which depends also on the poorly known properties of the Galactic magnetic field.

In Sec. 2, the rate of positron production from SNIa in the Milky Way bulge and disk is evaluated and compared to the observations. In Sec. 3, the morphology of the Galactic magnetic field is discussed (Sec. 3.1), as well as several aspects of the propagation of positrons in it (Sec. 3.2, 3.3 and 3.4); in particular, it is argued that positrons can escape from the disk into the bulge and annihilate

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there. The spatial morphology of the 511 keV emission resulting from such a transfer may, under certain conditions, be fully compatible with current observations. In Sec. 4 we show that the bulge/disk positron emissivity ratio may be as low as 0.5 and still compatible with SPI data. We substantiate that claim by calculating the resulting flux morphologies and intensities for several plausible distributions of the disk positrons, assumed to diffuse in a large volume (akin to the "Cosmic Ray Halo", occupied by ordinary cosmic rays). The existence of such a low surface brightness "Cosmic positron halo" could be put to test in a few years, as more data are accumulated in the SPI detectors; if it is confirmed, it will have important implications for our understanding of positron production, propagation and annihilation in the Galaxy (independently of the model of positron transfer from the disk to the bulge proposed here).

2. Positron production from SNIa in the Galaxy

A comprehensive overview of "conventional" positron production sites in the Galaxy has been presented in several places (Dermer and Murphy 2000, Prantzos 2004, Diehl et al. 2005, Knödlseder et al. 2005). The most prominent source of galactic positrons appears to be the β^+ radioactivity of supernovae (SN) and, in particular, beta decay of ^{56}Co produced in thermonuclear SN (SNIa). The peak luminosity of those objects suggests that they produce, on average, $\sim$0.7 M$_\odot$ of ^{56}Co ($\sim$1.5 10^{55} nuclei, releasing e$^+$ in $\sim$20% of their decays). However, because of the relatively short lifetime of ^{56}Co and of the poorly understood configuration of supernovae magnetic fields, theoretical estimates of the positron escape fraction f_{56} are extremely uncertain at present (e.g. Chan and Lingenfelter 1993). Observations offer, in principle, a much more reliable way to evaluate f_{56}, through the shape of the late optical lightcurve of SNIa. A pioneering study (Milne et al. 1999) of a sample of SNIa concludes that N$_{e^+}$=8^{+8}_{-4} 10^{52} positrons escape from an average SNIa, i.e. that f_{56} $\sim$3%. In the following, we shall adopt this as a canonical value, although a recent study of the thermonuclear SN2000cx (Sollerman et al. 2004), covering optical and near-IR wavelengths, concludes that its late lightcurve is compatible with f_{56} $\sim$0. However, as Sollerman et al. (2004) recognize, "...these conclusions are drawn from observations of a single SN, which was clearly unusual at the peak... and they have to be verified by more data..".

The next important ingredient in order to evaluate the e$^+$production rate in a galactic system is the SNIa rate R_{Ia}. Most previous studies evaluated that rate in terms of SN frequency per unit B-band luminosity (e.g. Cappellaro 2003), which is a a poor tracer of the stellar mass of a system. Mannucci et al. (2004) use the complete catalogue of near-IR galaxy magnitudes obtained by the 2MASS survey to evalute SN frequencies per unit luminosity in th near IR (which is a much better tracer of stellar mass), as a fuction of galaxian morphological type. They find that, in units of [100 yr 10^{10} M$_\odot$]$^{-1}$ (SNuM) R_{Ia} is : $0.044^{+0.016}_{-0.014}$ for E/S0, $0.065^{+0.027}_{-0.025}$ for Sa/b and $0.17^{+0.068}_{-0.063}$ for Sbc/d, i.e. a factor $\sim$4 higher in late spirals than in ellipticals. Note that those values are systematically higher (a factor $\sim$2) than previous estimates (e.g. in Cappellaro et al. 2003).

The last ingredient is the mass of the galactic system. In the case of the Milky Way bulge, various studies converge to values in the range 1-2 10^{10} M$_\odot$, either through photometric (e.g. Robin et al. 2004, Dwek et al. 1995) or dynamical (e.g. Klypin et al. 2003) determinations. We adopt M$_B$=$1.5^{+0.5}_{-0.5}$ 10^{10} M$_\odot$ in the following. Similar uncertainties exist in the case of the Milky Way disk (e.g. Boissier and Prantzos 1999, Robin et al. 2004). We adopt M$_D$=$4.5^{+1.5}_{-1.5}$ 10^{10} M$_\odot$ in the following.

The e$^+$ production rate from ^{56}Co radioactivity of SNIa is then:

$$S \ = \ M \ R_{Ia} \ N_{e^+}$$

In the case of the Galactic disk, clearly identified as a Sb/c spiral, one obtains S_D=$1.95^{+0.98}_{-0.93}$ 10^{43} e$^+$/s. [1] The Galactic bulge is usually assumed to have the morphology of an early type galaxy (E/S0) and in that case one obtains S_B=$0.17^{+0.083}_{-0.081}$ 10^{43} e$^+$/s. Those conservative estimates suggest that: 1) the bulge e$^+$ emissivity is between 0.06 and 0.16 of the one inferred from SPI mesurements; 2) the disk has $\sim$12 time more SNIa than the bulge, and correspondingly larger e$^+$ emissivity; 3) the disk emissivity is slightly larger than the total galactic (mostly bulge) emissivity required by SPI observations.

Thus, *assuming that the adopted N_{e^+} is correct*, one sees that SNIa in the Galaxy may indeed provide the positron emissivity required by observations; however, while theory suggests in that case a large Disk/Bulge ratio D/B $\sim$10, observations show exactly the opposite: D/B $\sim$0.2. This a standard problem encountered by almost any one of the suggested positron sources, with the exception of the dark matter and of the tangle of light superconducting strings; they cannot, in general, reproduce the morphology of the 511 keV emission observed by SPI, although some of them (e.g. X-ray binaries, microquasars) may encounter less difficulty than others. Note, however, that for most of those sources, their Galactic rates and positron emissivities are much more uncertain than for SNIa.

In fact, the problem may be even worse. As noted in Knödlseder et al. (2005), the disk emissivity may be entirely explained by the positrons released from the decay of ^{26}Al, a radioactive nucleus produced in massive stars, with a half-life of $\sim$1 Myr. Its characteristic gamma-ray line at 1.8 MeV has detected in the plane of the Milky Way by various instruments in the past 20 years (see Prantzos 1991, or Prantzos and Diehl 1996 and references therein), with a flux corresponding to the decay of $\sim$3 M$_\odot$ of ^{26}Al

[1] Errors are assumed to have gaussian distributions and add quadratically, but only M and R_{Ia} are used in the error calculation. Uncertainties of N_{e^+} are rather systematic and have not been taken into account. One may include them formally as e.g. S_D=$1.95^{+0.98}_{-0.93}\ ^{+1.95}_{-0.98}$ 10^{43} e$^+$/s.

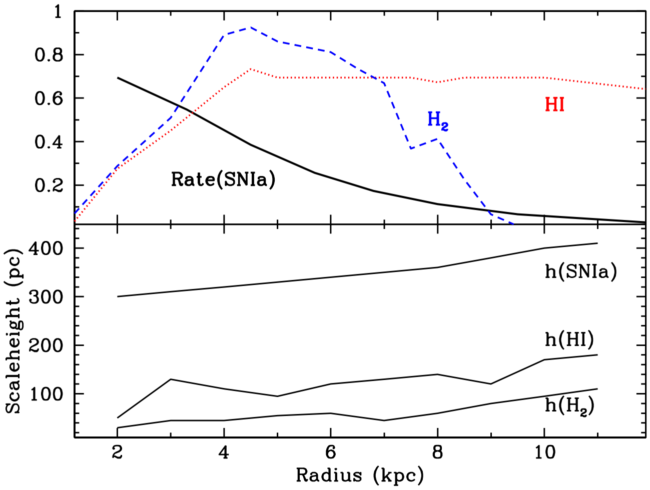

Fig. 1. *Top*: Radial surface densities of H_2 (*dashed* curve), HI (*dotted*) and SNIa rate (*solid*) in the Milky Way; the first two are expressed in $M_\odot/pc^2$ and in logarithmic scale, while the latter is in (Gyr $pc^2)^{-1}$ and in linear scale. *Bottom*: Scale heights of H_2, HI and SNIa as a function of galactocentric radius (see text for references).

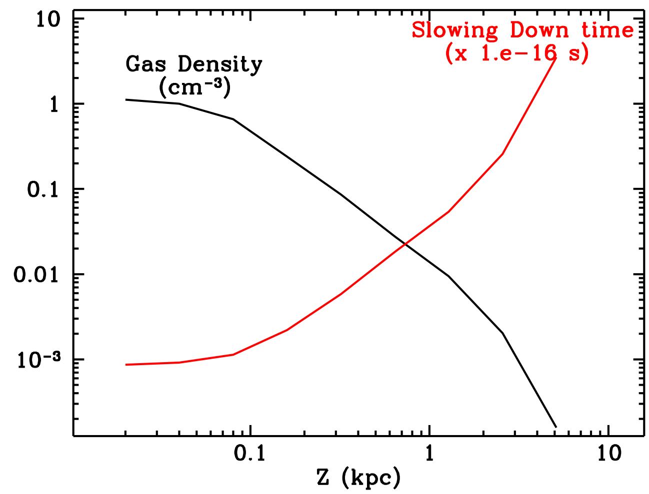

Fig. 2. Total gas density and timescale for positron slow down as a function of distance from the Galactic plane at galactocentric distance 8 kpc; curves for other galactocentric distances differ little from those ones. The timescale is calculated from the corresponding timescales for the various gaseous phases, i.e. $\tau_{SD}^{-1} = \Sigma(f_i \tau_i)^{-1}$, where i stands for cold neutral, warm neutral, warm ionised and hot ionised gas, and the corresponding density profiles and volume fiiling factors f_i are taken from Ferrière (1998).

per Myr. The corresponding positron emissivity could explain most (if not all) of the disk 511 keV flux, at least in the thin disk models tested by Knödlseder et al. (2005). However, as we argue in Sec. 4, the ^{26}Al positron emissivity may well be accomodated in the framework of the scenario proposed here, which involves an extended disk of positrons from other sources, like SNIa.

If the Galactic SNIa positron emissivity evaluated in this section is close to the real onen but the source of the observed bulge emission turns out to be different, it should then be a rather strange coincidence. We argue below that transport of disk positrons to the bulge through the Galactic magnetic field may inverse the Disk/Bulge ratio. The arguments are valid for any other source producing positrons of ~1 MeV, such as those resulting from radioactivity.

3. Positron propagation/annihilation in the Galaxy

In the Milky Way disk, the scaleheight of the most prolific e^+sources, namely SNIa, should be similar to the one of the old stellar population of the disk. Recent studies (e.g. Chen et al. 2001, Siebert et al. 2004) find H_* ~330-350 pc in the solar neighborhood, while in the inner Galaxy it is smaller but never drops below 300 pc (e.g. Ferrière 1998, Narayan and Jog 2002 and references therein). On the other hand, positrons slow down and annihilate in the gaseous medium of the disk, which has a smaller scaleheight (~100 pc in the solar neighborhood, Ferrière 1998). Fig. 1 summarises the relevant data (the profile of the SNIa rate is from the Milky Way evolutionary model of Boissier and Prantzos 1999).

Thus, a large fraction of the positrons released by the SNIa of the Galactic disk are found in a medium of substantially lower density n than the local Galactic plane. Radioactivity positrons have energies ~1 MeV and lose energy mostly through Coulomb interactions, with a characteristic timescale of τ_{SD} ~10^5 $(n/\mathrm{cm}^3)^{-1}$ yr (e.g. Forman, Ramaty and Zweibel 1986). For typical gas densities outside the neutral gas layer of the Milky Way disk, τ_{SD} is larger than 10^6 yr, as can be seen in Fig. 2 (calculated taking into account the various gaseous phases and corresponding volume filling factors of the ISM from Ferrière 1998). Thus, it appears that positrons of ~MeV energies resulting from SNIa radioactivity in the Milky Way disk wander mostly through a low density ISM for a couple of Myr, before thermalisation and annihilation (see also Sec. 3.2).

3.1. The Galactic magnetic field

During those long timescales, positrons move through the magnetic field (MF) of the Milky Way. The configuration of the Galactic MF is probed mainly through measurements of Faraday rotation of the radiation emitted by pulsars and extragalactic radio sources (e.g. Vallée 2004) and it is poorly known today. It appears though that the large scale regular MF is composed of a toroidal (disk) component (probably bisymmetric) and a poloidal (halo) component, probably in the form of a A0 dipole (see Han 2004 and references therein). For the latter component we adopt (Fig. 3) recent parametrisations (Alvarez-Muniz, Engel and Stanev, 2002; Prouza and Smida, 2003) expressing its cartesian (X, Y, Z) components in cylindrical coor-

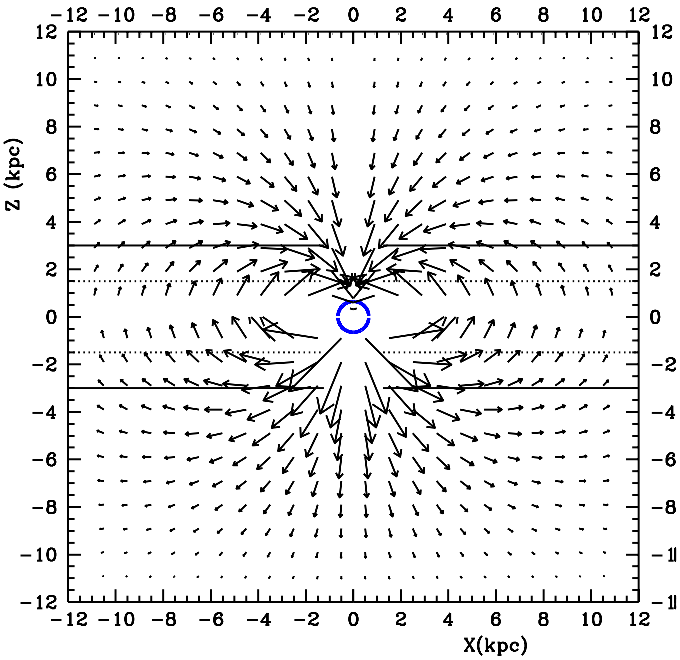

Fig. 3. A representation of the poloidal magnetic field of the Milky Way in the x-z plane, *assuming* it is a A0 dipole. The central circle corresponds to the size of the 511 keV emitting region (FWHM) seen by SPI aboard INTEGRAL. The irregular (turbulent) magnetic field *is assumed* negligible outside the region between the horizontal lines (*dotted* lines are suggested in Prouza and Smida 2003, while *solid* lines are lower limits to the cosmic ray halo size suggested in Strong and Moskalenko 2001); positrons escaping from that region are presumably directed by the dipole field lines towards the bulge.

dinates (r, θ, ϕ):

$$B_X = -3\mu_G \; sin\theta \; cos\theta \; cos\phi \; / \; r^3$$

$$B_Y = -3\mu_G \; sin\theta \; cos\theta \; sin\phi \; / \; r^3$$

$$B_Z = \mu_G \; (1 - 3 \; sin^2\theta) \; /r^3$$

where μ_G=184 μG kpc^3 is the magnetic moment of the Galactic dipole. At Galactocentric distance r=8 kpc the toroidal component has a strength of a few μG (Beck et al. 1996) and dominates the poloidal one (a few tenths of μG). However, the former varies as 1/r, while the latter as 1/r^3 and should therefore dominate in the inner Galaxy.

Positron propagation is strongly affected by the irregular (turbulent) component of the galactic MF, which is comparable in intensity with the regular one near the local disk. Unfortunately, the properties of the irregular component away from the disk plane are even less well understood than those of the regular components (e.g. Han 2004). In a recent work, Prouza and Smida (2003) assume that the turbulent component occupies 80% of the volume inside spiral arms, 20% of the volume outside spiral arms and within vertical distance $|z|$ <1.5 kpc and only 1% of the volume at larger distances. On the other hand, cosmic ray propagation models indicate that the size of the cosmic ray "halo" (CRH, i.e. the region inside which cosmic rays diffuse on inhomogeneities of the magnetic field) is $z_{CRH} > 3$ kpc, based on measurements of unstable/stable ratios of secondary nuclei (Strong and Moscalenko 2001). If e$^+$ escape from the CRH then positron propagation at large distances from the disk will be dominated by the regular MF, i.e. the poloidal field. In those conditions, a fraction of the positrons produced from disk SNIa will ultimately find their way into the bulge.

For the model to work, the positrons have to avoid the "mirror effect" (i.e. bouncing back in the gradient of the poloidal magnetic field as they approach the bulge), while conditions in the bulge much be such that positrons indeed annihilate there and do not escape it. Those questions are discussed in Sec. 3.3 and 3.4, respectively.

As mentioned in Sec. 1 the SPI data analysis by Knödlseder et al. (2005 and private communication) slightly favour a composite model, with a bulge positron luminosity of ∼1.5 10^{43} e$^+$/s and a disk luminosity of 0.3-0.5 10^{43} e$^+$/s; in fact, as we discuss in Sec. 4, bulge and disk luminosities of 1.2 10^{43} e$^+$/s each may be compatible with the data, provided the disk is sufficiently extended. In order to explain the observed bulge emissivity by the proposed model, the fraction of positrons channeled to the bulge must then be f_{ESC} ∼0.5 (taking into account the disk and bulge emissivities evaluated in Sec. 2), i.e. ∼10^{43} e$^+$/s from the disk have to join the 0.17 10^{43} e$^+$/s produced in the bulge and annihilate in that region.

3.2. Positron escape vs. confinement

A "naive", first order estimate of the escaping fraction of positrons f_{ESC} may be obtained by

$$\frac{f_{ESC}}{f_{CONF}} \sim \frac{\tau_{SD}}{\tau_{CONF}} \qquad (1)$$

where f_{CONF} is the fraction of positrons confined in the disk (f_{CONF}+f_{ESC}=1), τ_{SD} is the slow-down time for positrons and τ_{CONF} is their confinement time in the disk, in the framework of the Leaky Box model for cosmic ray propagation. Typical values are: for the positron slow down timescale at z=350 pc, τ_{SD} ∼1.5 10^6 yr (Fig. 2); and for the confinement time in the CRH τ_{CONF}=1.45±0.15 10^7 yr, a value obtained for normal cosmic rays (e.g. Mewaldt et al. 2001). Thus, a first estimate suggests that only ∼10% of the disk positrons may escape before slowing down.

We feel, however, that the many uncertainties of the problem require a much more detailed investigation and that a larger escape fraction cannot be excluded. For instance, reacceleration of e$^+$ by shock waves of SNIa may considerably increase τ_{SD}. Reacceleration seems "natural" (charged particles should be accelerated each time they encounter a shock wave) and is taken into account in some models of CR propagation (e.g. Strong and Moskalenko 1998, Ptuskin 2001). Note that in the case of standard CR (protons of energies ∼1 GeV) there is not much room

for reacceleration, just because of energetic arguments. Indeed, the kinetic power of Galactic CR is $\sim 10^{41}$ erg/s, i.e. a sizeable fraction of the kinetic energy released by Galactic supernovae ($\sim 10^{42}$ erg/s). However, the power in $\sim 10^{43}$ e^+/s (of 1 MeV each) is $P_{e^+} \sim 10^{37}$ erg/s. SNIa constitute about 20% of the total Galactic SN and collectively release a kinetic power a thousand times larger than P_{e^+}; thus, 1 MeV positrons may be reaccelerated many times and their slow-down time τ_{SD} largely increased.

On the other hand, the positron confinement time in the disk may be shorter than the standard value of τ_{CONF} $\sim 10^7$ yr. The reason is that, because of their low energy (and correspondingly low gyroradius in the Galactic MF) 1 MeV positrons may diffuse very little on the density fluctuations of the MF, and thus they may escape more easily than the higher energy particles of standard Galactic cosmic rays. Indeed, in the standard theory of resonant diffusion of charged particles on MF irregularities the condition for diffusion is that the particle gyroradius must be larger than the smallest scale of the fluctuations (and smaller than the largest scale). If it is smaller than the smallest scale, then diffusion is largely suppressed.

The gyroradius of 1 MeV positrons is $R \sim 10^9$ cm for a field of a few μG, like the one in the solar neighborhood. On the other hand, in the case of the local interstellar plasma, density fluctuations have been measured through pulsar scintillation techniques. Armstrong et al. (1995) find a firm upper limit of 10^{10} cm to the smallest scale, but they also stress that their measurements are compatible with even lower values. Thus, it appears that, within current uncertainties, the gyroradius of 1 MeV positrons may be smaller than the smallest scale of plasma fluctuations. Positrons may then diffuse hardly at all and leak easier from the confinement zone, i.e. their τ_{CONF} may be considerably reduced. Note that the measurements of Armstrong et al. (1995) concern mainly the local plasma, and the situation may be different away from the plane of the disk.

Those qualititive arguments are supported by a recent study of low energy positron propagation in the ISM by Jean et al. (2005). Their study concerns specifically the ISM of the Galactic bulge, but their results should also apply to the low density ISM away from the disk, which is mostly filled with hot ionized gas. The authors find that in such a medium positrons of $\sim$1 MeV can travel distances up to 5.5 kpc before they annihilate (their Fig. 6 and Table 4). Most of that distance (>90%) is covered while positrons propagate in the collisional regime, i.e. when they do not scatter in the irregularities of the MF. If positrons can cover such large distances, they can certainly escape from the "confinement zone" and reach the bulge, following the lines of the poloidal Galactic MF.

Quantitatively, the SPI measurements, combined with the theoretical SNIa disk and bulge emissivity (Sec. 2) require that $\sim$50% of the positrons escape from the disk and annihilate in the bulge (see Sec. 4 for a reassessment of SPI/INTEGRAL data implications). If the remaining 50% annihilates in the disk, the resulting Bulge/Disk emissivity ratio is $\sim$1.2, lower than the value of $B/D = 5^{+4}_{-2}$ obtained by SPI/INTEGRAL analysis in Knödlseder et al. (2005). However, as we show in Sec. 4, this is only because relatively thin disk configurations have been considered in the analysis of Knödlseder et al. (2005), whereas it is physically reasonable to assume that positrons annihilate in considerably larger volumes. An extended disk of low surface brightness can hardly be seen in current SPI/INTEGRAL data; Knödlseder et al. (2005) recognise that for the case of an extended halo and the argument holds similarly for a disk. On the other hand, the analysis of Jean et al. (2005) suggests that MeV positrons travel several kpc before anihilation, if the hot ISM fills a large fraction of the propagation volume (which is the case away from the disk). In fact, if a fraction of positrons escapes indeed the disk, as assumed here, it would be inconsistent to assume that the remaining annihilate close to their sources.

We conclude then that, in order to explain the SPI data, our model needs (Eq. 1) $\tau_{SD}/\tau_{CONF} \sim 1$ instead of the initially considered value of 0.10, while in Sec. 4 we argue that the SPI/INTEGRAL data are consistent even with B/D values as low as 0.5. In both cases, a large increase of τ_{SD}/τ_{CONF} above its "nominal" value is required. Such an increase could be obtained, for instance, by increasing τ_{SD} by a factor of 3 and simultaneously decreasing τ_{CONF} by a factor of 3. It is hard to evaluate whether such large modifications of τ_{SD} and τ_{CONF} are realistic or not. However we feel that, the favorable energetics for positron reacceleration and the large pathlength of positrons in hot ISM (Jean et al. 2005) indicate that this possibility is not unrealistic.

3.3. Can positrons enter the galactic bulge ?

If the configuration of the Galactic MF is indeed as assumed in Sec. 3.1, positrons that escape the cosmic ray halo are directed towards the bulge, spiralling and drifting along the lines of the dominant poloidal MF, with negligible energy losses. Whether they actually reach the bulge or not depends on the importance of the "magnetic mirror" effect they undergo in the strong gradient of the dipole MF. That effect is minimised if, when positrons enter the poloidal field, their velocity component $v_{||}$ parallel to the field lines is much larger than the corresponding perpendicular component $v_{\perp}$. Otherwise, most of them should be deflected backwards before reaching the bulge (as happens with electrons of the solar wind, entering perpendicularly the lines of Earth's magnetic field, which are trapped in the van Allen radiation belts).

It turns out that the condition $v_{||} >> v_{\perp}$ may be naturally achieved. When positrons are still in the cosmic ray halo, they diffuse on the turbulent component of the MF at small scales, but at large scales their diffusive motion follows the regular (toroidal) component. That kind of motion has been studied by Casse, Lemoine and Pelletier

(2002), who found that the components of the diffusion coefficient D parallel ($D_{||}$) and perpendicular ($D_{\perp}$) to the regular magnetic field B_0 are related by

$$\frac{D_{\perp}}{D_{||}} = \left[\frac{B^2}{B_0^2 + B^2}\right]^{2.3} \qquad (2)$$

where B represents the mean intensity of the inhomogeneous (turbulent) component. This implies that, even close to the disk (where $B \sim B_0$) $D_{\perp} \sim 0.2\ D_{||}$, whereas near the border of the diffusion zone (where $B < B_0$) one has $D_{\perp} << D_{||}$. In other terms, positrons diffuse essentially along the regular component of the MF. In consequence, their flux $J = -D\nabla n_{CR}$ (where n_{CR} is the cosmic ray density) is dominated by a component parallel to the lines of the regular magnetic field.

The configuration of the Galactic MF can only be continuous between the regions where the various components of the regular field dominate. The toroidal field changes smoothly into a poloidal one and positrons leaving the former enter the latter with a velocity essentially parallel to its field lines (since the component $v_{||}$ dominates their motion). For that reason, the magnetic mirror effect should be negligible and most positrons escaping the disk should find their way into the Galactic bulge.

3.4. Positron annihilation in the bulge

The amount of gas in the bulge and its properties (density, temperature, ionisation stage etc.) are very poorly known at present and it is hard to predict how the e^+ annihilation will take place, although the observed 511 keV line spectra give some hints to that (e.g. Guessoum et al. 2004, 2005; Churazov et al. 2005, Jean et al. 2005). Assuming that the bulge is ~10 Gyr old and has a mass of $\sim 10^{10}$ M$_{\odot}$, one finds that the mass return rate from old stars (red giants and AGB stars) is ~0.1 M$_{\odot}$/yr. That gas is expelled at relatively low velocities (a few 100 km/s), but it is hard to know the current gas density profile in the bulge, because the gas is dissipative and should slowly sink towards a gas torus in the galactic plane (from which new stars would occasionally form).

A lower limit to the gas mass in the bulge is obtained through analysis of infrared data (from IRAS and COBE/DIRBE) concerning the inner, or Nuclear, bulge by Launhardt et al. (2002). These authors find that ~2 10^7 M$_{\odot}$ of hydrogen reside in the Nuclear Bulge, out to a distance of ~200 pc from the Galactic center (mostly in an outer torus), while another ~4 10^7 M$_{\odot}$reside outside that region; in both cases the gas is mostly cold, dense, and clumpy in nature. Accounting for He and metals, the authors estimate the total gas mass in the central kpc (Central Molecular Zone) to 10^8 M$_{\odot}$. The presence of that gas may be explained by the action of the Galactic bar, driving gas from the galactic disk to the inner regions until the gas settles on stable orbits (e.g. Binney et al. 1991). However, part of it certainly originates from the gas slowly released by aging stars of the Bulge.

Assuming that the total gas mass in the bulge is indeed of the order of 10^8 M$_{\odot}$and fills a volume with a radius of 1-2 kpc, the mean gas density in the bulge should be n ~0.1-1 cm^{-3}. The average slow-down time scale of positrons in the bulge and the distance they travel before annihilation depend on the nature of the ISM and the volume filling factors of the various phases. Since the physical conditions of the bulge ISM are very poorly known at present, one has to turn the problem around and use the observed spectral signature of the e^+-e^- annihilation radiation to derive those conditions. This has been done in Jean et al. (2005) who find that the emission results from positrons annihilating in about equal amounts in the warm (T~8 000 K) neutral and ionized phases of the ISM. Their analysis also suggest that the fraction of annihilation emission from molecular and hot gas has to be less than 8% and 0.5%, respectively.

Those results imply that, either

i) the bulge ISM is dominated by the warm neutral and ionized phases, with the cold and hot phases having very small filling factors, or

ii) the bulge hot ISM dominates (as is the case in the solar neighborhood) but its morphology is such that positrons escape it and enter the warm and denser phases, where they annihilate, or

iii) the bulge hot ISM dominates and, since positrons cannot slow down and annihilate there, they mostly escape outside the bulge; only a small fraction of them enter the warm phase of the bulge and annihilate. The total rate of positrons going through the bulge is then much larger than indicated by the detected signal.

Obviously, case (iii), although physically plausible, exasperates the difficulty of finding a prolific positron source, able to provide a lot more than 1.5 10^{43} e^+/s.

Case (ii) is the one favoured in Jean et al. (2005). However, it is based on our understanding of the local ISM, while conditions in the bulge may be different. For instance, the density of heating sources of the bulge ISM (SNIa) is smaller than the corresponding one in the local disk (which is dominated by core collapse supernovae) and the volume filling factor of the hot ISM in the bulge may be much smaller than in our solar neighborhood. Case (i) may then be closer to reality.

In any case, the large magnetic field in the bulge (perhaps, up to 1mG, according to Morris and Serabyn 1996, and references therein) indicates an efficient confinement of positrons there, much more efficient than in the local disk. Thus, it is expected that positrons entering the bulge will be trapped and annihilate inside it (unless extremely special conditions, like e.g. a hot ISM with very large volume filling factor and/or peculiar configurations of the magnetic field, allow a large fraction of them to escape).

For illustration purposes we assume then that positrons in the bulge are annihilated in a gaseous medium which has a density profile similar to the stellar one, assumed here to be a simple exponential (i.e. no triaxiality is taken into account) with a characteristic scalelength R=0.32 kpc.

4. Disk surface brightness and Bulge/Disk ratio

In this section we discuss the disk emissivity profile from positron annihilation and the resulting Bulge/Disk emissivity and flux ratio. We assume that the Milky Way emissivity results from a bulge with emissivity L=1.2 10^{43} e^+/s (resulting from transfer of ∼50% of the disk SNIa positrons plus those produced by the bulge SNIa population) and from a disk with emissivity and morphology that are constrained from SPI measurements. For illustration purposes we adopt four different models for the disk:

Model A: The disk has an exponential profile, with scalelength of 2.6 kpc and scaleheight of 0.2 kpc. This is one of the two disk models adopted in the SPI data analysis of Knödlseder et al. (2005, model D1). It corresponds to an old (but not very old) disk and assumes that positrons annihilate close to their SNIa sources. The disk positron emissivity is L_A=0.4 10^{43} e^+/s, i.e. slightly less than half the remaining disk positrons (after the transfer of 50% to the bulge) annihilate in the disk near their sources, while the other half may escape completely from the disk; this model corresponds to the average disk emissivity allowed by the analysis of Knödlseder et al. (2005) for that morphology. It is used here as a check of our own modelisation against the work of Knödlseder et al. (2005). The Bulge/Disk ratio of that model is 3.

Model B: The disk has an exponential scalelength of 4 kpc and a scaleheight of 1 kpc. Those values reflect the assumption that positrons diffuse and annihilate away from their sources. In that case, their distribution at the moment of annihilation corresponds more to the distribution of cosmic rays. In fact, the scalelength of 4 kpc may be even too low, in view of the well known fact that the cosmic ray source distribution in the Milky Way has a surprisingly flat profile as a function of galactocentric radius (e.g. Strong and Moskalenko 1998). The positron emissivity of the disk is L=0.95 10^{43} e^+/s, i.e. it corresponds to the remaining ∼50% of the disk e^+ emissivity from SNIa. The Bulge/Disk emissivity ratio of this model is ∼1.3

Model C: This model involves two disks (beyond the bulge, which is common to all models): The first (Disk-B) is the same as in Model B; the second (Disk-C) has a short scaleheight of 0.1 kpc, a rather large scalelength of 5 kpc and a e^+ emissivity of L=0.3 10^{43} e^+/s. It illustrates the possible contribution from the decay of radioactive ^{26}Al. This isotope is produced mainly in massive stars, which are distributed essentially as the gaseous layer. The adopted e^+ emissivity corresponds to the amount of decaying ^{26}Al in the Galaxy, estimated to 3 $M_\odot$/Myr (e.g. Diehl et al. 2005). This configuration is the one of model D0 (young disk) adopted in the analysis of Knödlseder et al. (2005). It assumes that positrons from ^{26}Al decay do not travel away from their sources, since they propagate in a dense medium (an assumption which can be only partially justified, since ^{26}Al producing supernova heat the ISM; the emitted positrons encounter a hot ionized gas, at least in some directions, where they can propagate to large distances). The Bulge/Disk emissivity ratio of this model is ∼1.

Model D: The disk has larger scalength (6 kpc), scaleheight (3 kpc), and positron emissivity (L=2.4 10^{43} e^+/s) than Model B. It is used to show that Bulge/Disk ratios as low as 0.5 may be comptible with current SPI/INTEGRAL data, provided the disk is diluted enough.

Only Model A has a bulge/disk e^+ emissivity ratio compatible with the values obtained in SPI/INTEGRAL data analysis by Knödlseder et al. (2005), while the other ones are smaller. In all cases, the disk is truncated at an inner radius of 1.3 kpc (since it cannot physically co-exist with the bulge, see also Robin et al. 2004) and at an outer radius of 15 kpc (since cosmic ray acceleration sources do not exist at such large distances, see also Strong and Moskalenko 1998).

At this point one might argue that, even if positrons occupy a large volume, the 511 keV emissivity should be proportional to the product of their density times the electron (gas) density; this would result in a thin disk emitting 511 keV photons, not an extended one. However, positrons have a finite lifetime (the slow-down time t_{SD}, which is the sum of the lifetimes in diffusive and collisional regime) and in that respect they could be assimilated to radioactive particles: during that period they can travel away from their sources (in the hot ISM) and fill a large volume, but once their lifetime has "expired", they annihilate locally. In that case, *the resulting 511 keV profile reflects the distribution of positrons* and not the product of their density times the gas density.

The 511 keV flux profile of the Galaxy, in longitude l and latitude b, is calculated by integrating the volume emissivity $\rho(r, l, b)$ of the various model components (bulge plus disk) along the line of sight

$$dF(l, b) \; = \; \int_0^\infty \rho(r, l, b) \; dr \; dsinb \; dl \qquad (3)$$

where r is the distance from the Sun (e.g. Prantzos and Diehl 1996). Bins of 0.5 deg are used for both longitude and latitude. The volume photon emissivity $\rho_\gamma(r, l, b)$ (in photons cm^{-3} s^{-1}) is related to the positron emissivity $\rho_{e^+}(r, l, b)$ (in e^+ cm^{-3} s^{-1}) by

$$\rho_\gamma \; = \; [2(1-f) + \frac{1}{4} \; 2 \; f] \; \rho_{e^+} \qquad (4)$$

where f is the positronium fraction. This expression translates the fact that positrons may annihilate either directly, with a probability (1-f), giving 2 photons of 0.511 MeV, or after positronium formation with probability f. Positronium is formed 1/4 of the time in the singlet $^1S_0$ state (which gives again 2 photons of 0.511 MeV) and 3/4 of the time in the triplet $^3S_1$ state (which gives 3 photons with energies covering the range 0-0.511 MeV).

The gamma-ray flux is calculated by assuming that the positronium fraction is f=0.93, as in the analysis of Knödlseder et al. (2005); note that the recent spectroscopic analysis of the SPI data by Jean et al. (2005) suggests f=0.967±0.022, which changes the resulting fluxes

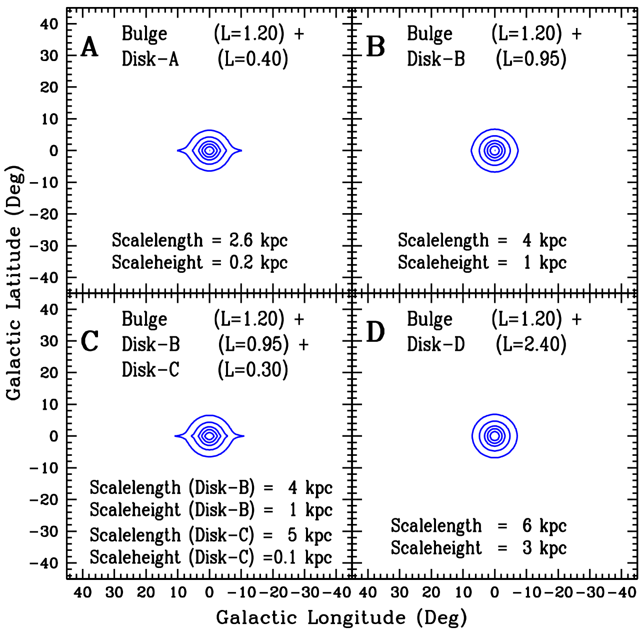

Fig. 4. Simulated profile of the 511 keV emission of the Milky Way in galactic coordinates. In all panels, L represents positron emissivity in units of 10^{43} e^+/s and the last isoflux contour represents 16.7% of the peak central flux. In each panel, letters (A, B, C, D) indicate models described in Sec. 4. All those models have the same bulge emissivity (L=1.2), assumed to result from the transfer of 50% of positrons from disk SNIa (plus the ones produced in the bulge, see text) and they differ only by the disk properties (emissivity, scalength and scaleheight) as indicated in each panel. In all panels, bulge positrons are annihilated locally in the bulge. In panel A, disk positrons are also annihilated locally, i.e. near their sources (SNIa, distributed as the old stellar population); this model, with a disk positron emissivity L=0.4, corresponds to the disk found in SPI data analysis (its morphology corresponds to D1 in Knödlseder et al. 2005). In panel B, positrons occupy a "Cosmic ray disk" of large scalelength and scaleheight (see text), with a positron emissivity L=0.95, i.e. half of the disk SNIa positrons; this disk would be invisible with currently available SPI exposure. In panel C, a second disk, of small scaleheight (similar to disk D0 of Knödlseder et al. 2005) is added to the configuration of panel B; such a disk would correspond to positrons emitted by Galactic ^{26}Al (L=0.3) and locally annihilated, and it is marginally detectable in current SPI data. Finally, Panel D is as Panel B, but the disk is more luminous (positron emissivity L=2.4, i.e. Bulge/Disk=0.5) and more diffuse than in case B; despite its luminosity, it is also "invisible" with current SPI sensitivity.

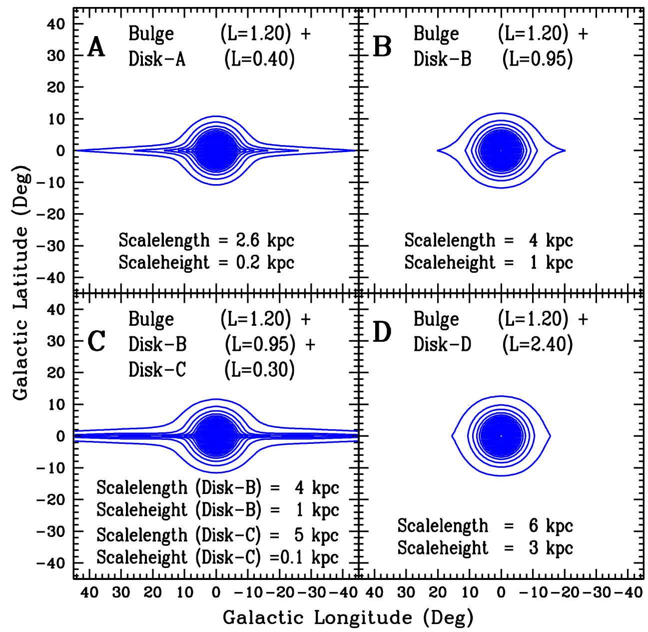

Fig. 5. Same as Fig. 4, but the outmost isocontour corresponds to 4% of the maximal flux, i.e. sensitivity is improved by a factor of 4 w.r.t. Fig. 4. The disks are clearly detected in cases A and C, but only marginally detectable in cases B and D.

by 10%: for f=0.93, Eq. (4) leads to ρ_γ=0.6 ρ_{e^+}, where for f=0.967 one obtains ρ_γ=0.54 ρ_{e^+}.

In all cases, the total positron emissivity of a galactic component (bulge or disk) occupying a volume V is normalised to the assumed value of L, i.e.

$$L \ = \ \int_V \ \rho_{e^+} \ dV \tag{5}$$

The results of our simulations appear in Fig. 4, where the properties of each model also appear in the corresponding panel. Isocontours are drawn at equal levels (in linear scale) corresponding to 1/6 of the peak central flux (i.e. the outer contour is at 16.7% of the peak flux). Assuming that the peak flux in the central 3 square degrees is $\sim$4 10^{-4} cm^{-2} s^{-1} (see Fig. 7), the outmost contour corresponds to a flux of $\sim$7 10^{-5} cm^{-2} s^{-1}. This corresponds approximately to the current sensitivity of SPI/INTEGRAL for an extended source at 511 keV (Knödlseder et al. 2005).

It can be seen that in case A (already tested in Knödlseder et al. 2005), the disk is marginally detectable, whereas in Cases B and D the disk is "invisible" with current SPI sensitivity. Case C is also interesting, since both a thin and a thick (and more luminous) disk can be compatible with current data.

Fig. 5 shows the effect of increasing sensitivity (by a factor of 4) for the same model configurations. The outmost contour is at 4% of the central flux and now the disks are clearly seen in cases A and C. There are hints for a disk in Case B and indications for a flattened bulge in case D. Clearly, deeper observations of the Milky Way

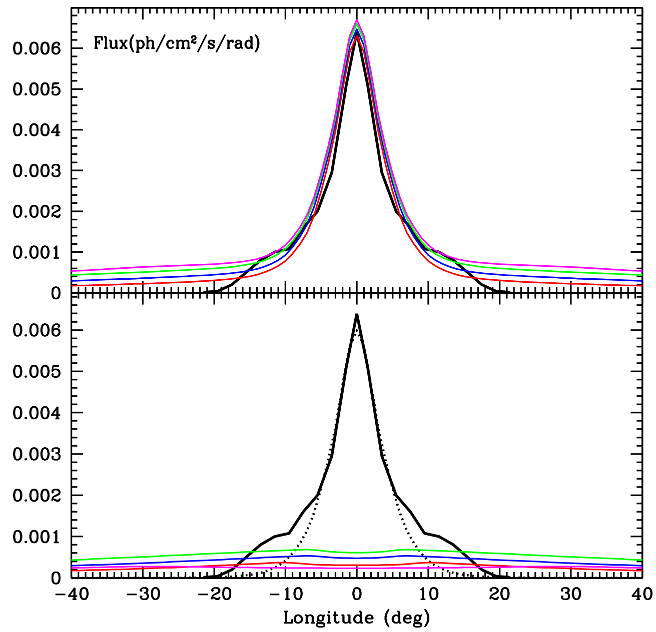

Fig. 6. Flux in the 511 keV line as a function of Galactic longitude, corresponding to the configurations of Figs. 4 and 5. In both panels, the thick solid curve is the one derived from SPI data analysis (Knödlseder et al. 2005, Fig. 5); it is centered to l=0^o and assumed symmetric w.r.t. the Galactic center. In the upper panel, the combined flux of each model is given, while in the lower panel, the flux from each individual component is given; the *dotted curve* in the lower panel represents the bulge component, common in all models. In order to reproduce exactly the results of Knödlseder et al. 2005 (their Fig. 5), fluxes are integrated in latitude, for $|b| < 30^o$.

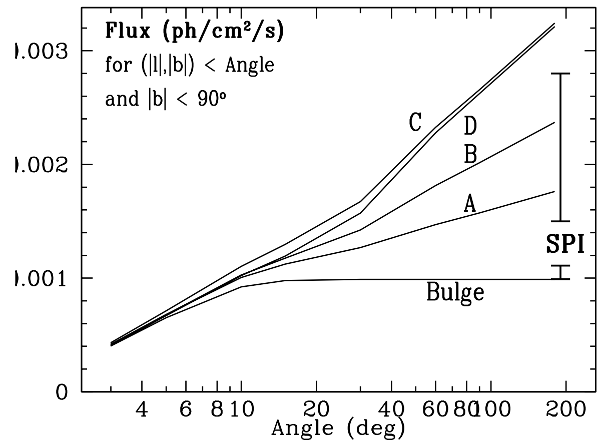

Fig. 7. Flux in the 511 keV line inside longitude l and latitude b, such as : $|l|$, $|b|$ <Angle, as a function of Angle ($|b|$ runs from 0^o to 90^o and $|l|$ runs from 0^o to 180^o). Curves indicate results of our modelling, for the adopted bulge and models A, B, C and D, respectively. The results from the SPI data analysis (Knödlseder et al. 2005) are displayed for the full range of their composite models (*upper vertical line*) and for the corresponding bulge component only (*lower vertical line*), integrated over 4 π.

are required to understand the various aspects of positron propagation in the Milky Way.

Fig. 6 displays the corresponding fluxes as a function of Galactic longitude. They are integrated in latitude, for $|b| < 30^o$, to be directly comparable to the data displayed in Fig. 5 of Knödlseder et al. (2005). In the upper panel the combined fluxes are given (i.e. those directly corresponding to Figs. 4 and 5), while in the lower panel, the fluxes of individual components are displayed; the latter allows, in particular to appreciate the contribution of the bulge component, always dominating the inner $\pm 12^o$ of longitude. All models give flux profiles compatible with the SPI data. The differences concern mostly the region outside $|l| \sim 20^o$, where the extended and more luminous models C and D display larger fluxes than models A and B; still the differences are well within the uncertainties of current SPI data.

Finally, Fig. 7 displays integrated fluxes from square regions of the sky centered on the Galactic center, i.e. for $(|l|, |b|) <$Angle A, as a function of A ($|b|$ runs from 0^o to 90^o and $|l|$ runs from 0^o to 180^o). Differences between the various models appear more clearly in that diagram. They are negligible for $(|l|, |b|) < 10^o$, of the order of 15% for $(|l|, |b|) < 20^o$ and they reach a factor of 2 when integration in the full $(|l|, |b|)$ range is performed (i.e. over 4 π). The latter case, at Angle=180^o, is compared to the range of models fitted to SPI/INTEGRAL data by Knödlseder et al. (2005, vertical error bars on the right). Models A (already tested in Knödlseder et al. 2005) and B (with a bulge/disk ratio of 1.2 only) are well within the current measurement uncertainties. Models C and D have slightly larger total fluxes (by 10%) but only because such extended disks have not been used in the SPI data analysis in Knödlseder et al. (2005).

5. Summary

In this work, we investigate several aspects of the positron annihilation line observed in the Milky Way, and we propose a model that satisfies the current observational constraints.

In Sec. 2 we reassess the positron production rate from SNIa, on the basis of recent data. We find that (a) the combined bulge+disk production is slightly larger than required by observations, but (b) the bulge/disk ratio is the inverse of what is observed, *if positrons are assumed to annihilate close to their sources*. Point (a) may be just a coincidence (i.e. SNIa may not be the Galactic positron sources), but it is argued here that there is a way to reconcile points (a) and (b).

It is suggested that about half of the disk positrons may escape the disk and be transported via the Galactic magnetic field to the bulge, where they annihilate. In Sec. 3.1, the (still poorly known) configuration of the Galactic

MF is presented briefly; the existence of a strong poloidal component, suggested by recent data, is crucial to the success of the model. In Sec. 3.2, some aspects of the propagation of positrons in the hot and low density ISM far from the disk are considered; in such conditions positrons (even of MeV energies, such as those produced by radioactivity) may travel for several kpc before slowing down and annihilating. They may then escape the disk and be chanelled to the bulge by the poloidal MF of the Galaxy, which dominates away from the disk. In Sec. 3.3 it is argued that positrons may enter the bulge avoiding the mirror effect (due to the MF gradient), since their motion is always dominated by a velocity component parallel to the MF lines. In Sec. 3.4 the annihilation of positrons inside the bulge (where the configurations of the MF and of the ISM are also poorly known) is discussed.

In Sec. 4 we calculate sky maps of the 511 keV emission, based on various assumptions about the extent of the positron annihilation region. It is argued that, in general (and in the framework of our model, in particular) positrons have to annihilate away from their sources. We show quantitatively that the SPI/INTEGRAL data are fully compatible even with bulge/disk positro emissivity ratios lower than 1, provided that sufficiently (but not unreasonably) extended positron distributions are considered. We stress, in that respect, that positrons can be assimilated to radioactive particles (due to their finite slowdown time), so that *the resulting 511 keV profile reflects the distribution of positrons* and not the product of their density times the gas density.

Thus, SNIa may indeed be the dominant positron source in the Milky Way, as thought for many years. The rates, positron yields and galactic distribution of other candidate sources (e.g. X-ray binaries, millisecond pulsars, microquasars etc.) are much more poorly known than those of SNIa. However, if SNIa turn out to produce much less positrons than claimed in Sec. 2, the arguments of Sec. 4 may be used for any other positron sources, which have sufficiently large yields but not the correct bulge/disk ratio. Indeed, if the positron yields of some of those sources are large enough, the fraction required to be transferred to the bulge may be small (and even zero, i.e. the positrons of the disk have just to move sufficiently far away and even escape the Galaxy, in order for their annihilation to be undetectable).

The model proposed here relies heavily on our poor understanding of the Galactic magnetic field and of the propagation of low energy positrons in it. However, its assumptions may be tested, through future observational and theoretical developments. Systematic multi-wavelength studies of SNIa, including the infrared, will determine ultimately the typical positron yield of those objects. A small 511 keV emission outside the bulge is currently seen by SPI/INTEGRAL (Knödlseder, private communication) and, given enough exposure, the spatial extent of that emission will be determined (either by INTEGRAL or by a future instrument); an extended disk emission will prove that positrons travel indeed far away from their sources. Finally, the morphology of the Galactic magnetic field, and especially the presence of a poloidal component, will be put on more sound basis through further measurements (e.g. Han 2004).

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